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Physics-Based Seismic Hazard Simulations and 3D Velocity Structure Models for Southwest British Columbia

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ABSTRACT

The state-of-the-art in seismic hazard analysis is the incorporation of deterministic source and wave propagation effects using physics-based three-dimensional (3D) ground motion simulations. Physics-based 3D ground motion simulations are conducted using parallelized finite-difference wave propagation algorithms and high-performance computing for large magnitude crustal and inslab earthquake rupture scenario models within 3D seismic structure models of southwest British Columbia. Cascadia megathrust interface scenarios were simulated by the University of Washington's M9 project. Ambient noise tomography (ANT) studies are achieved to update the regional 3D shear-wave velocity (Vs) model for southwest British Columbia up to 60 km depth. Deployment of 19 short-period seismometers in Metro Vancouver for 60 days was accomplished to improve the resolution of the new 3D Vs model in the upper-most kilometers beneath Metro Vancouver. In addition, the geodatabase compiled by the Metro Vancouver seismic microzonation mapping (MVSMM) project was used to generate higher-resolution 3D models (< 1 km depth). A 3D seismic layer thickness model of the region's four major seismic layers (post-glacial and glacial sediments, and Georgia basin sedimentary and Coast Mountain plutonic rocks) is developed from 1,215 lithologic logs and existing interpreted geologic 2D cross-sections. In addition, a 3D Vs model is developed from 777 Vs depth profiles and merged as a 'geotechnical layer' within the regional 3D Vs model of southwest British Columbia. All relevant datasets are compiled and input to Seequent LeapFrog Geo software to use geostatistical spatial interpolation to build the Metro Vancouver 3D models. The MVSMM project achieved over 2,000 microtremor horizontal-to-vertical spectral ratio (MHVSR) measurements across Metro Vancouver at an average 800-m grid resolution; previous studies have verified MHVSR amplification is consistent with low-level earthquake recordings available in the region. The developed 3D seismic-layer-thickness and Vs models are queried at select MHVSR locations to provide 1D Vs-depth models to calculate theoretical SH-wave site amplification for validation with the measured horizontal-to-vertical (H/V) amplification. This process is used to confirm if the developed 3D seismic structure models are consistent with (will predict) measured seismic site effects (seismic microzonation).

Keywords: Physics-based ground motion simulation, 3D wave propagation simulations, 3D velocity model, 3D geology model, Greater Vancouver, Ambient noise tomography, Basin effects, Basin Amplification

INTRODUCTION

Three-dimensional (3D) ground-motion simulations are playing an increasingly important role in assessing seismic hazards. The simulations provide a means for incorporating complex rupture and geologic effects that are important but difficult to capture in traditional, empirical ground-motion models. Whereas the underlying physics of seismic wave propagation is well understood, the accuracy of the ground-motion simulations is limited by our knowledge of the elastic and anelastic (nonlinear and attenuation) properties of earth materials, which are usually described by 3D seismic velocity models, often referred to as community velocity models (CVMs). CVMs are a key ingredient for the physics-based simulation of ground motion in earthquake-prone regions, also called deterministic earthquake ground-motion simulations.

The Pacific Northwest 3D velocity model (v1.3) of Stephenson [1] had been used as the base elastic structure model in several physics-based earthquake ground-motion simulation studies [2-4]. The model spans from northwest WA to southern British Columbia, with dimensions of ~1100 km NS (40.2°N to 50°N) by ~600 km EW (122°W to 129°W) by 60 km Up-Down and a spatial uniform-grid resolution of 250 m. The model incorporates continental and oceanic sedimentary basin, crust, and mantle units. The minimum Vs was set to 625 m/s, representative of a Pleistocene glacial (stiff) sediment surface. The latest version of the CVM model (v1.6) [5] was used in recent Cascadia M9 simulations [6]. The model has a 500 m spatial resolution. Inside continental sediments, both P- and S-wave velocities were updated based on geological and geophysical information about the Quaternary and Tertiary deposits, including borehole data, seismic surveys, and the time-averaged shear wave velocity to 30 m (Vs_{30}) measurements in the USA. The Cascadia subduction interface was modeled after data from earthquake locations and seismic velocity studies [7; 8]. Molnar [9] developed a refined version of the original Cascadia CVM (called Georgia basin CVM) inside the Georgia basin and Puget Sound regions, which is available in 250 m resolution. The Georgia basin CVM includes a more accurate description of the velocity structure (in the upper 1 km for the Georgian basin region) in southwest British Columbia [3; 4], which is derived from local geological and geophysical datasets and the higher-resolution local tomography model of Dash et al. [10]. The Georgia basin is elongated in a NW-SE orientation, with depths of < 3 km NW and < 7 km SE of Greater Vancouver. In all community velocity models, up to 300 m of Holocene deltaic sediments of the Fraser River in southern Greater Vancouver are not included. The surface of the 3D basin model therefore represents over-consolidated Pleistocene glacial sediments or stiff soil sites. This is a significant limitation to modelling of the potential earthquake ground motion and the overall amplitude and duration of simulated ground motions in the Georgia basin are likely underestimated where lower velocity sediments are missing from the model. This limitation is mitigated by performing 1D site response analyses [11].

Molnar et al., [3; 4] used earthquake recordings of the 2001 moment magnitude (M) 6.8 Nisqually, WA, earthquake, the only suitable earthquake recordings at the time, for calibration of the simulated long-period ground motions using the Georgia basin CVM. The average factor of PGV overprediction in the Georgia basin region is 2.1 for the [1] velocity model and 1.6 for the updated velocity model; incorporation of high-resolution shallow seismic data in the basin velocity model results in an average 24% reduction in bias of predicted PGV. Later, Ghofrani and Molnar [12] used the observed ground motions of the 2015 M 4.7 Vancouver Island earthquake to validate the Georgia basin CVM. The available recordings of this earthquake provided a significant opportunity to re-evaluate source characteristics and regional attenuation from a moderate magnitude inslab earthquake that originated within the subducting JdF plate, as well as local variations in the shaking related to geology and site effects in southwestern B.C. [13]. Ghofrani and Molnar [12] showed that including the physical structure model could result in over 10 times larger predicted peak ground motions in comparison to the predicted background peak motion ($PGV_{Basin}/PGV_{Non\text{-}Basin}$). The validation exercises conducted using the Georgia basin CVM confirmed overprediction of 3D synthetic ground motions.

A key component of the seismic microzonation mapping project for Metro Vancouver, B.C., includes further updating and improving the resolution of the Georgia basin CVM, specifically in the Metro Vancouver area, by incorporating Vs depth profiling information at over 800 locations of *in situ* invasive or non-invasive field Vs profiling testing and other *in situ* measurements that can be converted to Vs using region-specific empirical relationships (e.g., ~900 cone penetration tests, ~530 standard penetration tests, and ~2350 microtremor horizontal-to-vertical (H/V) spectral ratio measurements) from the project's comprehensive regional geodatabase [14; 15]. Characterizing (shallow) Vs layers is of critical importance for recently deposited materials (e.g., alluvial basins), because these materials tend to have the lowest velocities and therefore the greatest potential for seismic (de)amplification, soil non-linearity, and/or liquefaction (pore water pressure dissipation). Additionally, recognition of and/or mapping the major features of the deeper geological layers and determining the shape and dimension of a basin are essential in improving the realistic generation of synthetic earthquake ground motions.

Ambient (seismic) noise tomography (ANT) has recently become a well-established velocity mapping technique (e.g., [16-18]). Unlike traditional earthquake-based tomographic methods, ANT does not require heterogeneously distributed earthquake sources. In addition, the high-frequency spectral content of the ambient noise makes this technique ideal for high-resolution imaging of velocity structures at crustal and uppermost mantle depths (e.g., [19]). In recent years, the rapid expansion of global, regional, and local broadband seismograph networks has promoted its widespread adoption. Recent improvements in seismic data distribution and management, as well as computational capabilities, have provided the means for processing the large volumes of ambient seismic noise data needed for this method. The first continental-scale study of the crust and upper mantle Vs structure of Canada and adjacent regions using ambient noise tomography was presented by Kao et al., [20]. Surface wave tomography inversion was carried out from the dispersion data to estimate the phase and group velocity distribution at each 1° increment in latitude and longitude for periods between 5 and 100 s. For each grid point, a 1D Vs profile was inverted from the dispersion data and the resulting Vs profiles were then combined into a pseudo 3D Vs model that extended down to ~100 km depth. This national scale model does not provide sufficient resolution for 3D earthquake wave propagation simulation.

Shallow subsurface velocity structures, particularly Vs, have a significant influence on strong ground motions. Typically, regional tomographic models produce a low-resolution image of shallow depths, resulting in overestimated near-surface velocities. Recognizing this issue, developing a (near-surface) geotechnical layer (GTL) is a way to adjust the velocities from regional models to agree with Vs_{30} mapping. In a recent effort for simulating M9 megathrust earthquakes in the Cascadia subduction zone, Roten et al., [21] derived velocities and densities in their computational mesh by extending the regional Cascadia CVM (v1.6; [5]) to 150 km depth and embedded a more detailed model of shallow velocities [9] in the Georgia basin. In the near surface part, they used a recent empirical correlation between geomorphic terrain classes and measurement based Vs_{30} values for the Pacific Northwest [22] to define a geotechnical layer. No other current velocity model includes a geotechnical layer for southwest BC.

Using decades of data, more recent seismological methods, and inversion approaches, we are developing a high-resolution 3D Vs model of southwest British Columbia, focused particularly on the Georgia basin region, that reveals the complex tectonic architecture of the region alongside a meaningful representation of the model uncertainty. This paper focuses on the advancements in 3D velocity modelling in southwest British Columbia (≤ 60 km) and specific to development of a 'geotechnical layer' (≤ 2 km) in the Metro Vancouver region.

REGIONAL 3D VELOCITY MODEL OF SOUTHWEST BRITISH COLUMBIA

Stage 1

We performed a preliminary surface wave tomography study centred to southwest British Columbia using existing earthquake and ambient noise data recorded by 625 seismic stations in the past two decades (Figure 1a). The inter-station distances range from 3 - 200 km. Ambient seismic noise data have a sampling frequency of 1 Hz and are from 625 seismic stations. We used magnitude (M) 5+ earthquakes at epicentral distances of 10°-120° and depths up to 50 km. Surface wave signals were retrieved by performing cross-correlation of daily ambient noise records and earthquake waveforms recorded by station pairs connected on the same great-circle path following the method described in Ojo et al. [23]. Subsequently, we measured fundamental-mode phase and group velocity dispersions using the automatic frequency-time analysis (AFTAN) technique (e.g., [24]) and 2D tomographic inversion at periods of 4 - 40 s following the ray theory method described by Barmin et al. [25]. We jointly invert group and phase velocity dispersion data extracted from the tomographic maps at 0.125° x 0.125° grid spacing for one-dimensional (1D) Vs model using the neighborhood algorithm [26; 27] from surface to 60 km depth (Figures 1b).

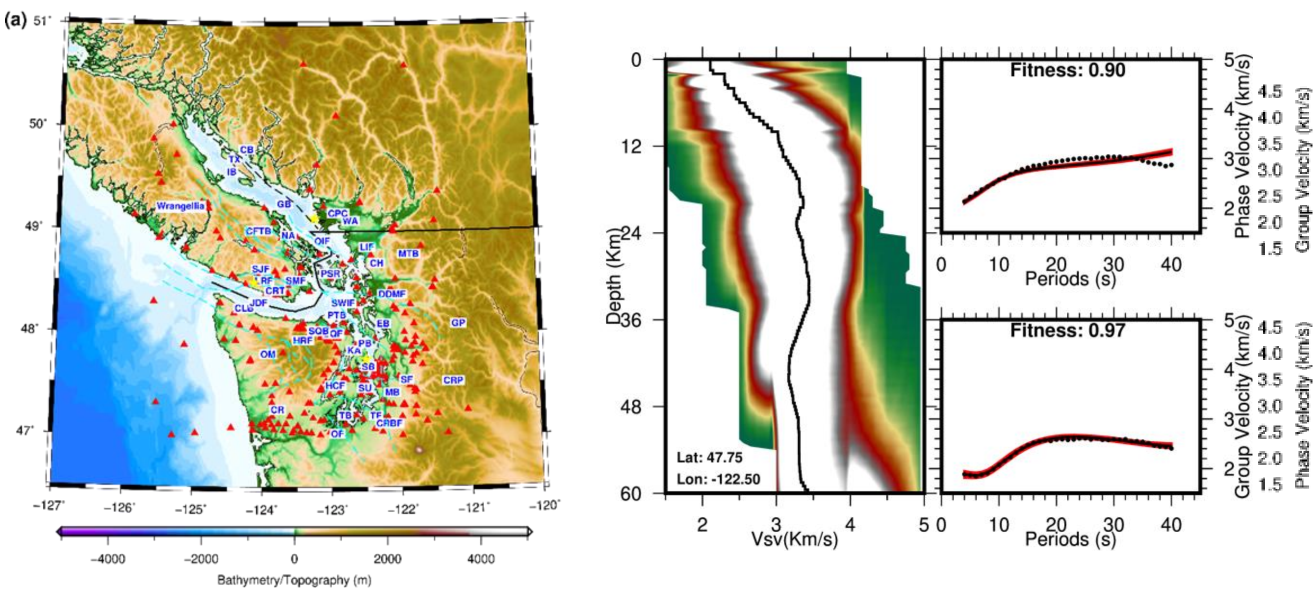

Figure 1. (left) The topographic map of the study area overlaid by seismic stations (red triangles) and labels of important geological features described in Ramachandran et al. [28] and (right) an example 1D inversion on Vancouver Island (Longitude: -122.5˚E, Latitude: 47.75˚N).

Finally, we interpolate the 1D models across depths to obtain an ANT 3D Vs model of the study area (Figure 2). The 3D Vs model reveals: (1) anomalous low-velocity in the Puget sound region down to mantle depths largely attributed to subduction dehydration processes and trapped fluid-rich sediments; (2) characteristic low-velocity beneath large sedimentary basins delineating their geometry and depth extent; (3) evidence for deep-seated crustal faults on Vancouver Island marked by segmented high-velocity structure; (4) high-velocity oceanic slab subducting southeastward beneath the Olympic Peninsula characterized by anomalously slow upper mantle velocity, and (5) localized high-velocity layer in the upper crust straddled between low-velocity seismic reflectors attributed to mafic remnants of magmatic processes. Our new 3D Vs model provides direct constraints on shear-wave velocities (previous tomographic models converted Vp to Vs) and significantly extends the area for high-resolution images, allowing for a more holistic evaluation of the seismic hazard potential in the entire region.

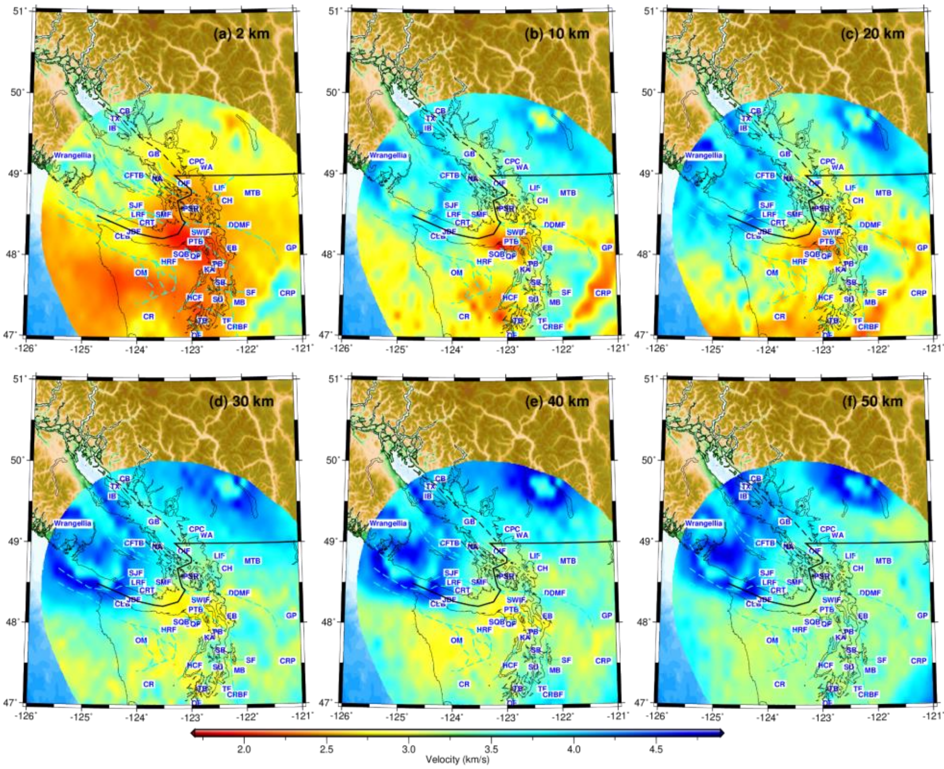

Figure 2. Depth slices of the ANT 3D Vs model at (a) 2, (b) 10, (c) 20, (d) 30, (e) 40, and (f) 50 km plotted over the topographic map of the study area. Results are only shown for regions with excellent resolution based on ray path density.

Stage 2

To advance development of the ANT 3D Vs model and achieve improved resolution in the upper ~10 km, we deployed 19 seismometers throughout Metro Vancouver (Figure 3) to densify the existing seismic networks and associated ray paths between seismic stations. The 19 seismometers are a combination of 5 broad-band seismometers (Nanometrics 20s posthole) and 14 short-period seismometers (4.5 Hz three-component geophone).

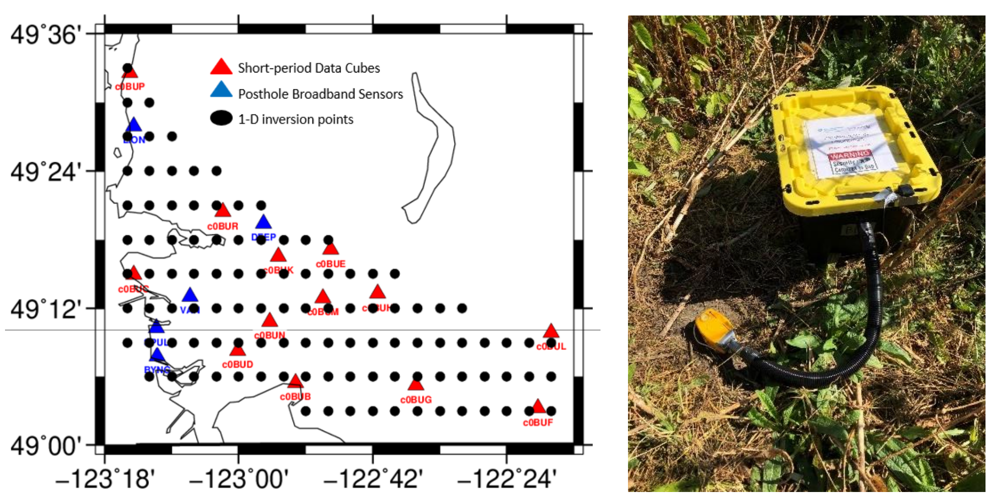

Figure 3. (left) Distribution of seismic stations included in Stage 2 and (right) example short-period seismometer deployed in the field.

The 19 seismometers are installed primarily outdoors for a near-continuous 60-day recording period between August 29 to November 11, 2022. Additional ambient noise recordings were retrieved from 112 seismic stations that are active in the deployment window (see Figure 3). Following the workflow described in Stage 1, we retrieved 8126 cross-correlations and dispersion datasets which were added to our existing database and implemented to develop an improved ANT 3D Vs model of southwest BC. The analysis is still ongoing for processing and integrating these new data, and therefore updating the 3D ANT Vs model.

METRO VANCOUVER 'GEOTECHNICAL LAYER' 3D VELOCITY MODEL

The geology of Metro Vancouver is quite variable. Topographic and simplified geologic maps of western Metro Vancouver are shown in Figure 4A, B. The youngest Holocene deposits in the region are modern alluvial, deltaic and bog deposits. The Fraser River delta, south of Vancouver, is a topographically lowland region (Figure 4A) comprising deltaic silts and sands, with thickness up to 300 m [29]. A 500 m thick Pleistocene succession underlies the Fraser River delta's center [30; 31] and displays complex changes in sediment types, vertically at individual sites and laterally between them. Pleistocene sediments as shallow as 19 m are found beneath central Lulu Island [32]. However, on western Lulu Island, the Pleistocene surface is more than 300 m deep [33]. These Pleistocene sediments are mostly composed of ice-compacted till present at or near the surface across most of Vancouver and Burnaby and glaciomarine and glaciofluvial sediments [34]. The Holocene-Pleistocene sediment package overlies the Late-Cretaceous Georgia basin sedimentary bedrock and pinches out to the north, from a maximum thickness of 800–1000 m beneath Ladner to only several meters at the edge of the delta [30]. At the southernmost tip of the Coast Mountain range, which is located in northern Metro Vancouver, pre-Tertiary plutonic igneous rocks are exposed at the highest altitudes. The Late-Cretaceous Georgia sedimentary basin outcrops in the North Shore (0 m) and dips southward at 5-10° beneath Vancouver reaching ~200 m depth north of the Fraser River and ~800 m beneath Ladner [30].

Geological, geophysical, and geotechnical data are fundamental data inputs (i.e., geodata) for seismic microzonation hazard mapping. Essential types of geodata for earthquake shaking (i.e., amplification) hazard mapping include seismic velocities, densities, fundamental site frequencies, and nonlinear soil behavior (e.g., shear modulus reduction and damping curves, stress-strain hysteresis model). A main objective of the MVSMM project is development of a comprehensive 3D geodatabase to determine seismic material properties of the major geologic units [14; 15]. Geodata compilation for the MVSMM project is accomplished via two independent but parallel avenues: (1) from previously collected available and private geodata sources, and (2) by performing field-based (*in situ*) multi-method non-invasive seismic testing across the region [35]. In avenue 1, open geodata resources of the federal, provincial, and municipal governments were compiled first (2017-2019), including topographical and geological maps (Figure 4A, B), stratigraphic logs of the BC water well online database, and the Geological Survey of Canada's compilation of over 500 velocity depth profiles in the Fraser River delta [36]. We then requested and compiled private geodata from 24 local geoconsultants, government agencies, stakeholder groups, and engineering firms during 2018-2022. Digitization of shared paper- or image-based data was accomplished when required. The majority of the geodata from avenue 1 came from invasive *in situ* methods (e.g., borehole stratigraphy, cone penetration testing (CPT), downhole seismic, and seismic cone penetration test (SCPT)) and geotechnical laboratory tests of discrete soil samples [14]. Specific geodatasets of the project's geodatabase are shown in Figure 4, displaying geodata locations with known depth to glacial till (Fig. 4D) and Vs depth profiles (Fig. 4E). In avenue 2, the MVSMM project facilitated supplementing avenue 1 geodata with multi-method non-invasive *in situ* seismic testing techniques such as active-source Vp and Vs refraction and multichannel analysis of surface waves (MASW) methods and passive-source ambient vibration array (AVA) and microtremor H/V spectral ratio methods [35]. The project's compiled geodatabase is a crucial and comprehensive resource that offers a full and current repository of geospatial data in the western Metro Vancouver region, allowing users to quickly assess, manage, and make decisions based on the accurate and reliable data contained therein. Its extensive coverage of geo characteristics and layers, including topography, hydrology, geology, and geophysics makes it a useful resource for professionals and scholars working in a variety of sectors ranging (e.g., urban planning, risk reduction, disaster response). The MVSMM project geodatabase comprises ~10,000 lithology logs, ~800 Vs profiles, ~1380 CPT, ~530 SPT, and ~2375 peak site frequencies from microtremor H/V amplification spectra.

Increasing computing power and the development of improved geological software have led to the geoscientific community utilizing 3D (volume) modeling in geologic technology development. Generation of 3D geomodels using Leapfrog Geo 3D modelling software [38] have been accomplished for seismic microzonation mapping purposes in the St. Lawrence Lowlands [39] and Saguenay, Québec [40]. Similarly, we utilize the comprehensive 3D geodatabase of the MVSMM project to develop a 3D "geotechnical layer" block model with four major seismic-impedance-based geologic surfaces (corresponding to postglacial, glacial, Tertiary sedimentary rock and Pre-Tertiary igneous rock groupings) and Vs data. In Leapfrog Geo 3D, mathematical interpolants of the radial basis function are used to produce 2D surfaces between measurement points of the input 1D data logs [41] to generate the 3D model. We input ~1200 1D logs that indicate post-glacial thickness to the depth of glacial till (z_{gl}) and ~900 1D logs that indicate postglacial and glacial thicknesses to the depth of bedrock (z_{rk}) to build our 3D seismic geology block model (4 surfaces). To generate a 3D "geotechnical layer" Vs model, we input 685 Vs depth profiles to build the 3D Vs model (11 selected surfaces) using spheroidal interpolation of the radial basis function. Leapfrog Geo's software uses spheroidal interpolation as a method for radial basis function (RBF) interpolation [42]. The size and shape of the spheroids are determined by a centre point and a set of axes. The RBF is then built as the total of several spheroids, each of which is centred at a distinct data point and weighted based on how far away it is from the interpolation point. This spheroidal interpolation is a strong technique for interpolating data in geological and geophysical models and is commonly used in the mining and exploration industries [43-45]. It offers a versatile and precise method of data interpolation and can be applied to accurately model complex geological features.

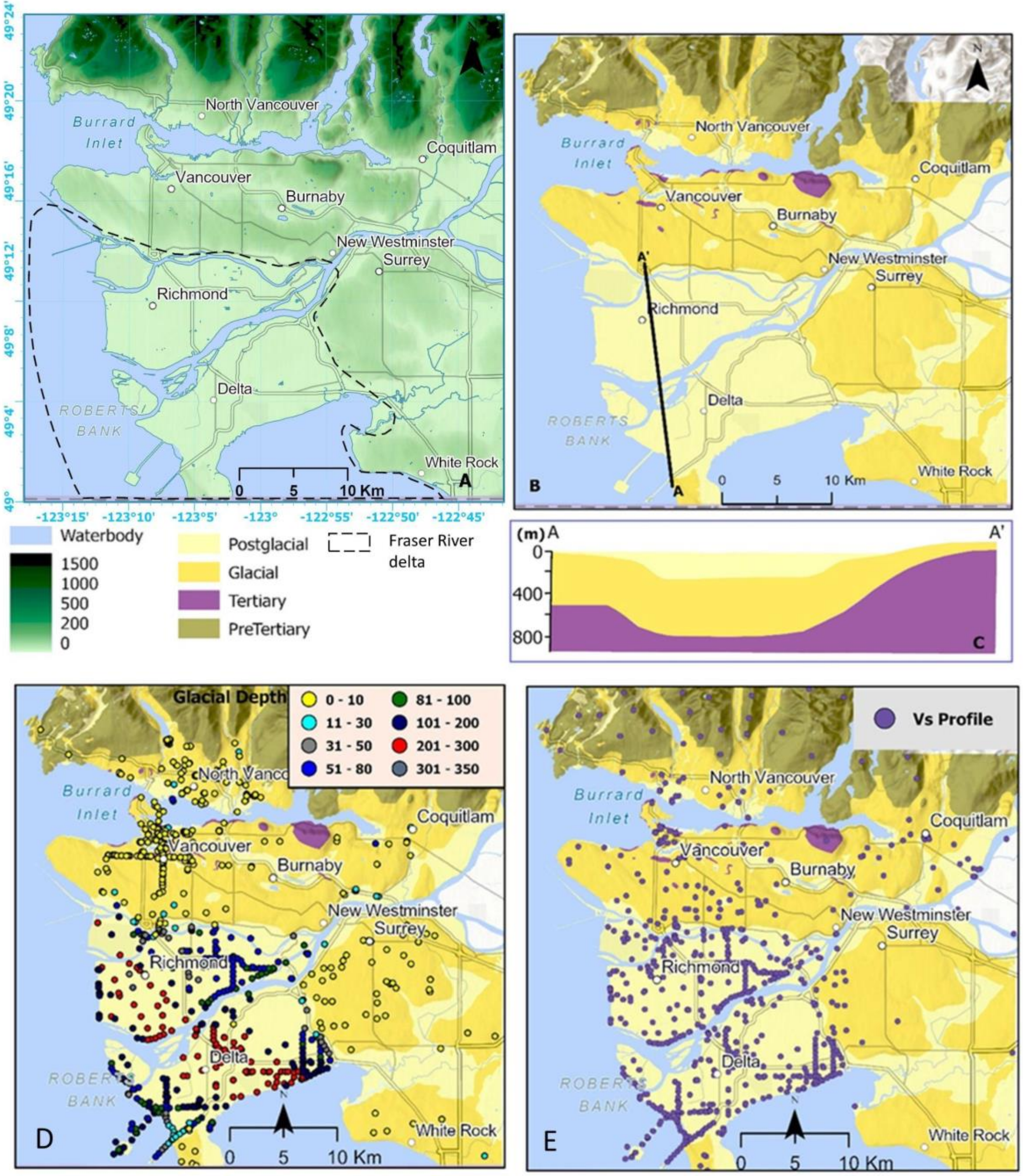

Figure 4: (A) Topographic digital elevation model (DEM; in meters) of the study region. Dotted line defines surface limits of the Fraser River delta lowlands. (B) Simplified surficial geologic map and (C) A-A' geologic cross section (modified from Rogers et al. [29]). (D) Borehole locations (circles) with known depth of glacial till (colours). (E) Locations of ~800 Vs depth profiles.

A selected cross-section from our developed 3D seismic geology model is shown in Figure 5, coincident with the northwest-southeast trending C-D' cross-section (Figure 5A) of Clague et al. [37]. Black filled circles at the top of the Clague et al. [37] cross-section C-D' indicates the locations of the 1D stratigraphic borehole logs used in generating the geologic cross-section

(Figure 5B). Similarly, we indicate the locations of 1D logs that are within 200 m of the C-D' transect from our 3D seismic geology model (Figure 5C; our model also includes all the 1D logs used by Clague et al., [37]). Overall, our automated 3D seismic geology model identifies similar thicknesses of post-glacial and glacial surfaces as the Holocene and Pleistocene interpreted geologic surfaces of Clague et al. [37]. Postglacial sediment thickness rapidly deepens from a few meters in West Vancouver (northwestern limit, location C) to up to 300 m in the Fraser River delta (intersection with A-B' section and southeastward). The similarity between our seismic geology and Clague et al. [37]'s interpreted geologic cross-section is not serendipitous, as we input several virtual 1D logs of this cross-section into our model.

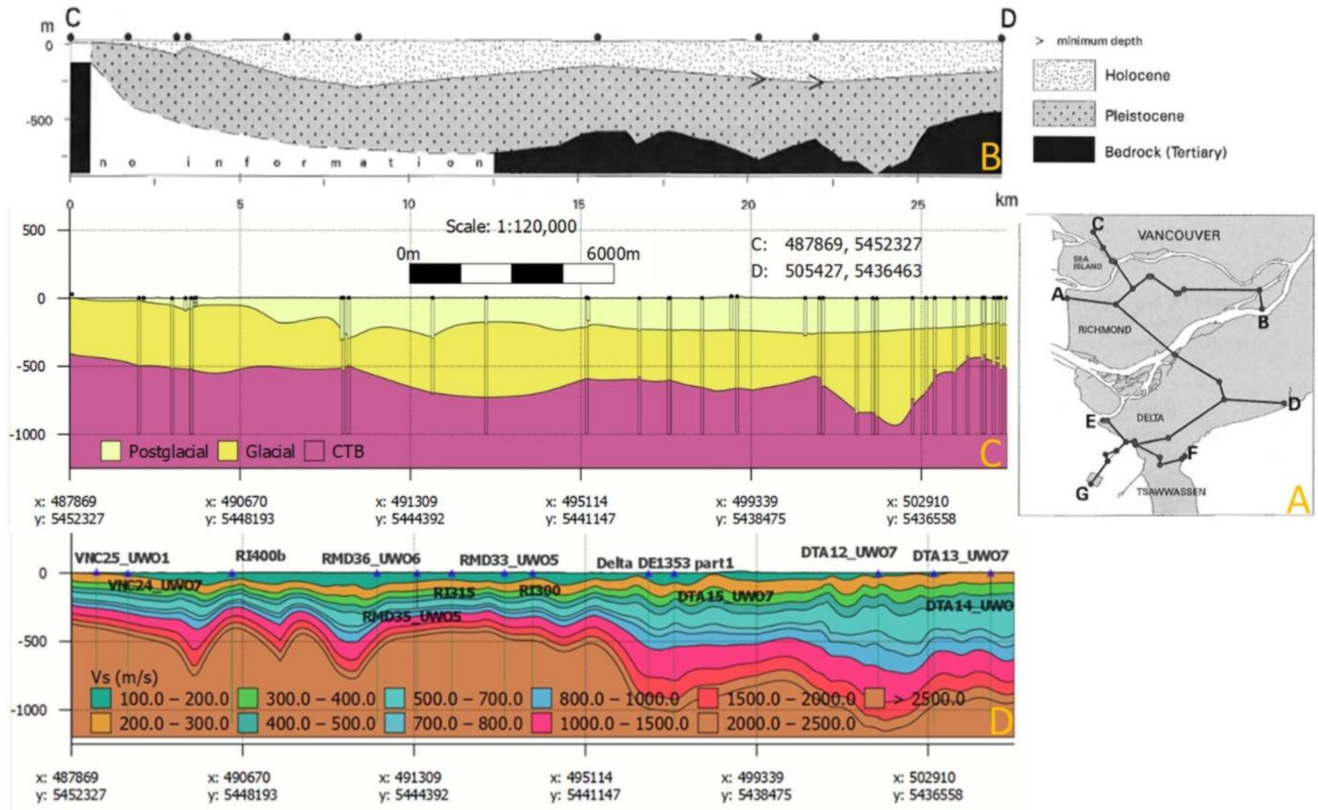

Figure 5. (A) Location of the northwest-southeast trending CD' cross section. (B) Interpreted geology CD' cross-section of Clague et al. [37]. (C) CD' cross-section from our 3D seismic geology model. (D) CD' cross-section of our 3D Vs model. Blue triangles show locations of single station MHVSR measurements.

Figure 5D shows the C-D' cross-section of our 3D "geotechnical-layer" Vs model. The 11 Vs surface horizons (100 to 2000 m/s) of this model are independent of the above seismic geology model but should be similar since the four chosen 'geology' units are based on the four major seismic impedance contrasts in the region. At the surface, the Vs of the Quaternary postglacial sediments ranges from 100-500 m/s over the 300 m depth range with a mean Vs of 239 m/s and one standard deviation of 87 m/s. Underlying glaciated sediments consist primarily of ice-compacted till and glaciomarine silts and sands from numerous glaciations. Vs of glacial sediments ranges from 280 m/s (at surface) to 1162 m/s (700 m depth) with an average Vs of 543 m/s with one standard deviation of 140 m/s. The average Vs of Tertiary rock is 1295 m/s with one standard deviation of 460 m/s and of Pre-Tertiary rock is 1710 m/s with one standard deviation of 600 m/s.

Validation of the geotechnical layer 3D model

The MVSMM project collected 2350 microtremor H/V spectral ratios at an approx. 600 to 1000 m grid spacing across the region. Each Fourier H/V amplification frequency spectrum provides peak frequencies and associated amplification related to seismic impedance contrasts; the default assumption is that the lowest H/V peak frequency (f_{0HV}) is a measure of the fundamental-mode site frequency (f_0, inverse of site period) [46]. We seek to validate our 3D models via comparison of the independently measured microtremor H/V amplification with 1D site amplification predicted from 1D seismic geology and Vs models extracted at the same location within our 3D models. We selected all 13 single-station microtremor measurement sites that are within 300 m of cross-section C-D' (blue triangles in Figure 5D). At each microtremor site, we extract the thickness of each seismic geology unit (layer depths) and the 1D Vs model from the 3D models. 1D site amplification is predicted as the transverse shear-wave transfer function for the average Vs of each layer (two-to-three-layer Vs models, as applicable), termed amplification model M. We also validate the 3D seismic geology (thickness) model, independent of the 3D Vs model, by using the regional average Vs for the given seismic geology layer (i.e., 239 m/s and 543 m/s for post-glacial and glacial layers, respectively) to predict 1D site amplification, termed the general amplification model G. Agreement in f_{0HV} is most sensitive to agreement in sediment layer thicknesses, whereas agreement in A_{0HV} is most sensitive to agreement in Vs, noting agreement in measured H/V and 1D modelled amplification is an ongoing research subject [46]. Thus, we concentrate evaluation of the 3D model's performance in predicting f_0 (1D site amplification) compared to f_{0HV} (measured microtremor H/V amplification).

Table 1. Evaluation of the absolute difference (Hz) and relative percentage change (%) in f_{0HV} for the 1D site amplification model M and general amplification model G compared to measured f_{0HV} for 13 sites along cross-section C-D'. Pink (blue) shading indicates over (under) estimation of f_{0HV}.

Site	f_{0HV}	Model M	abs. diff	% change	Model G	abs. change	% change
VNC25	0.63	0.35	0.28	44	0.30	0.33	52
VNC24	0.24	0.30	0.06	25	0.30	0.06	25
RI400	0.76	0.76	0	0	0.70	0.060	8
RMD36	0.19	0.20	0.01	5	0.20	0.01	5
RMD35	0.19	0.25	0.06	32	0.20	0.01	5
RI315	0.29	0.30	0.01	3	0.20	0.09	31
RMD33	0.25	0.25	0	0	0.20	0.05	20
RI300	0.25	0.35	0.10	40	0.40	0.15	60
DEI353	0.23	0.25	0.02	9	0.23	0	0
DTA15	0.23	0.25	0.02	9	0.20	0.03	13
DTA12	0.23	0.25	0.02	9	0.25	0.02	9
DTA13	0.28	0.25	0.03	11	0.23	0.05	18
DTA14	0.25	0.30	0.05	20	0.25	0	0
	Average		0.05	16		0.07	19
	Std. Dev.		0.07	15		0.09	19

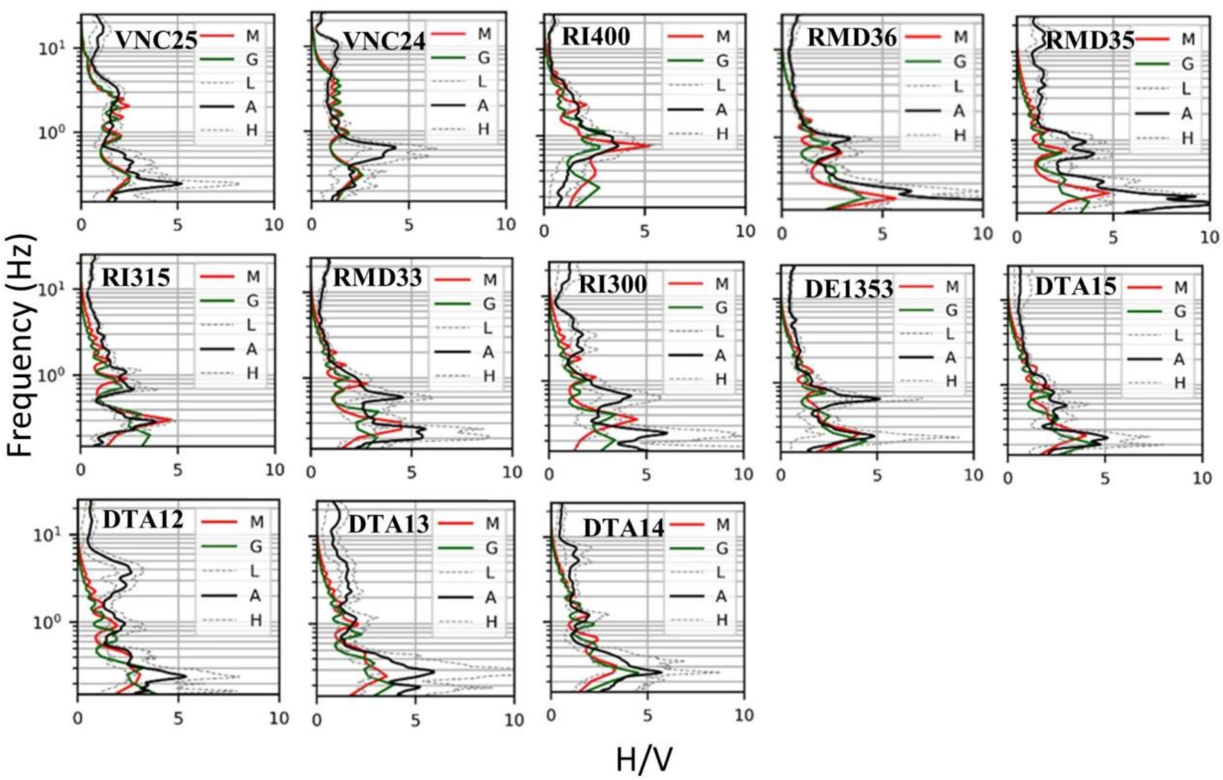

Figure 6. Comparison of the measured average microtremor H/V amplification (black line) and one standard deviation (dashed lines) with 1D site amplification predicted using the 3D thickness and Vs models (red line) and the 3D thickness model with V_{Sav} of the geologic layer (green line).

Figure 6 shows comparison of the measured microtremor H/V amplification with the two 1D site amplification models. There appears to be reasonable agreement in f_{0HV} and A_{0HV}, noting modelled A_0 is primarily lower amplification than measured A_{0HV}.

Table 1 shows that the 1D site amplification model M tends to overpredict f_{0HV}, whereas the general amplification model G tends to underpredict f_{0HV}. There is evidence that the 1D site amplification model M is more accurate (average absolute difference of 0.05 Hz and 16% relative change in f_{0HV}) than use of only the regional average Vs combined with 3D model soil thicknesses (model G).

INTEGRATION OF REGIONAL 3D MODELS FOR 3D WAVE PROPAGATION SIMULATIONS

We will merge the ANT 3D Vs model of southwest BC with the Georgia basin CVM (version 1, [9]) to generate version 2 of the Georgia basin CVM. We plan to use the Georgia basin CVM (version 1) as the initial model for the inversion of phase and group velocity dispersion curves and iteratively improve it through ANT. Considering the inter-station distances and ray path densities, the resulting ANT 3D Vs model will reveal structures and thereby improve the Georgia basin CVM (version 1) at depths > ~2 km (or equivalently at periods > 2-4 s). In addition, the developed 3D geotechnical layer (seismic geology and Vs) models for the Metro Vancouver region will be merged with the Georgia basin CVM (version 2) to improve resolution at shallow depths (< 1 km). Both models need to be discretized at a spatial resolution that retains their essential information (e.g., 200 m) before merging. This will be done using geostatistical interpolation (linear or kriging). To merge these two models, we will apply a smoothing function (e.g., depth-dependent Gaussian filter) to soften the edges where two models are overlapping. We expect that the final model shows higher resolution and significantly stronger velocity contrasts than the initial model, specifically at intracrustal and Moho depths. It is also expected that the final model reveals new features and precise features that existed in the initial model.

CONCLUSIONS

Improving the regional 3D physical structure (velocity) model of southwest British Columbia requires multiple independent studies (different resolutions or depth scales) at significant expense and expertise (multi-year, multi-equipment, multi-discipline, multi-personnel). Two significant achievements in updating the Georgia basin CVM are highlighted here: (1) ANT is performed to update the regional 3D Vs model for southwest British Columbia up to 60 km depth, and (2) development of a geotechnical layer based on a comprehensive regional geodatabase compiled by the MVSMM project to improve the resolution of the CVM at depths of < 1 km.

To achieve ANT, we used over two decades (2000 - 2021) of continuous ambient noise and earthquake data recorded by temporary and permanent seismic stations within the northern CSZ. We retrieved dispersion datasets following the ambient noise cross-correlation and earthquake two-station methods and inverted them for Vs perturbations at depths. We performed tomographic inversion to obtain the 2D variation of the group and phase velocities in the study area at periods of 4 - 40 s. We utilized ANT techniques to update the regional 3D Vs model for southwest BC. Deployment of 19 short-period seismometers in Metro Vancouver for 60 days was accomplished to improve the resolution of the new ANT 3D Vs model in the upper-most kilometers beneath Metro Vancouver. We generate the first 3D Vs model via ANT (previous 3D Vs models were converted from Vp) that reveals detailed images of the lithospheric structures consistent with known geology and previous studies.

The geodatabase compiled by the MVSMM project is used to generate higher resolution “geotechnical layer” 3D models (< 1 km depth) specific to the western Metro Vancouver region. A 3D seismic layer thickness model of the region’s four major seismic layers (post-glacial and glacial sediments, and Georgia basin sedimentary and Coast Mountain plutonic rocks) is developed from 1,215 lithologic logs and existing interpreted geologic 2D cross-sections. In addition, a 3D Vs model (< 1 km depth) is developed from 777 Vs depth profiles (i.e., ‘geotechnical layer’). All relevant datasets are compiled, and geostatistical spatial interpolation is used to build the Metro Vancouver 3D seismic geology and Vs models.

We will integrate the updated ANT 3D Vs model of southwestern British Columbia (< 60 km depth) with the geotechnical layer 3D Vs model of western Metro Vancouver (< 1 km depth) to create the highest resolution region-specific Vs model. With these updates, the previous Georgia basin CVM's resolution at different depth levels and scales will be significantly improved. The developed 3D seismic geology layer thicknesses and Vs models were queried at select microtremor H/V locations to provide 1D Vs-depth models to calculate theoretical SH-wave site amplification for comparison with the measured HV amplification. The results from this process are used to confirm if the developed 3D seismic structure models are consistent with (will predict) measured seismic site effects (seismic microzonation).

With the hybrid/multi-component CVM that we are developing, we will have the highest resolution Vs model of the southwest British Columbia (including Georgia Basin) that offers great potential for deciphering a 3D seismic geology model of the crust of the region. This model will be required to undergo extensive validation exercises including comparison with the limited number of recorded earthquake ground motions. Considering that this model has a more precise description of the subsurface geological and velocity structures at different depth levels, it will have a great impact on the reliability of the future numerical wave propagation simulations, improving ground motion prediction, and the accurate understanding of earthquake ground motion related hazards in southwestern British Columbia.

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